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Pipeline deformation monitoring using distributed fiber optical sensor

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ABSTRACT

Deformation of long distance pipeline takes place more easily under the various adverse factors such as freezing-thaw and earthquake, and oil and gas often leak from the broken pipeline once the deformation has exceeded a previously established threshold. In order to solve the hot issue on the pipeline deformation monitoring, this research was launched on the basis of the combination of distributed fiber optical sensor and conjugate beam method. One finite element model of a pipeline with the length of 50 m and one PVC (Polyvinyl Chloride) pipeline with the length of 4 m were constructed to validate the deformation method, respectively. The finite element pipeline model was loaded vertical displacement at different positions simultaneously, and the PVC pipeline was gradually applied different level of loads at the midspan. In the two tests, the continuous or distributed strain data and the discrete strain data were used to calculate the deformation of the pipeline based on the conjugate beam method. In order to validate the deformation monitoring method, a comparison between the displacement curve calculated by the distributed strain data and that calculated by the discrete strain data was conducted. The results of the two tests indicate that the deformation of the pipeline can be well monitored and the method can be applied to the field applications.

1. Introduction

With the rapid development of economy, the demand for the oil and gas is increasing in the world, and the long-distance pipelines have been one of the most important energy transport facilities. Long-distance pipelines, especially the buried pipelines, have inevitably crossed through complex geological environment, which always suffer from natural (freezing – thaw, earthquakes) or man-made disasters. Over time, these factors can lead to damage such as large deformation and leakage, which always cause major accidents and environmental pollution. Therefore, monitoring techniques to detect deformation of pipeline are vital to the safety of the pipeline operation [1–3]. Pipeline deformation can be evaluated through the measuring strain of pipeline. Conventional deformation measuring methods such as fiber Bragg grating sensor-based deformation monitoring methods can not cover the global deformation due to their limited strain location monitoring [4,5]. Furthermore, the locations of large deformations or strains in a long distance pipeline are not known a priori. Qiu et al and Zhu et al have used pipeline inspection robot to monitor the deformation or leakage of buried pipeline, respectively. Their studies can directly detect the pipeline deformation or leakage, but they have shortcomings of consuming an enormous amount of time and affecting oil and gas transportation [6,7].

In the past decade, distributed Brillouin optical fiber sensor has emerged as a viable technology for structural health monitoring of infrastructures, which has the superior performance in comparison with conventional sensors in measuring strain and temperature, and being widely used in field projects [8–12]. In the fields of pipeline safety monitoring, Ding et al proposed a method for pipeline deformation calculation based on the relation expression between the deformation and the distributed strain, and have obtained some good results [13]. Jia et al designed a kind of Brillouin optical time domain analysis (BOTDA) strain sensor to realize pipeline leak detection, which was packaged by one sensitive material to crude oil and the oil leak can produce expansion stress on the BOTDA strain sensor [14]. However, the accuracy and sensitivity of stress is strongly affected by the leakage, and the sensing performance will decrease once the sensitive material has sucked up a lot of oil.

In this paper, the distributed fiber optical sensor was used to monitor the deformation of long distance pipeline and the common conjugate beam method (CBM) was used to calculated the displacement from the strain measurement. In order to validate the deformation measuring method, one finite element model of

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pipeline, which was applied multipoint displacement simultaneously, with the length of 50 m was constructed. In the deformation analysis, different strain sets chosen from the compressive and tensile strain distribution at the top and bottom surfaces of the pipeline calculated by the finite element analysis. Furthermore, one PVC pipeline model with the length of 4 m was conducted to validate the method, the discrete strain data measured by electric resistance strain gauges and the distributed strain data measured by the Brillouin optical fiber sensors were used to calculate the deformation based on CBM. In this work, the number of the distributed strain data is much larger than that of discrete strain data and the calculating quality of the pipeline deformation is dependent on the number of the strain points.

2. Introduction of distributed Brillouin optical fiber sensing technology and conjugate beam method

2.1. Principle of distributed Brillouin optical fiber sensing technology

The Brillouin effect is the scattering of a lightwave by an acoustic wave, and the Brillouin frequency shift is proportional to the refractive index of the optical fiber and the local velocity of the acoustic wave. This relationship can be expressed as

$$\upsilon_B = 2n\upsilon_A/\lambda_p \tag{1}$$

where υ_B denotes the Brillouin frequency shift, n denotes the refractive index of the optical fiber, υ_A denotes the he local velocity of the acoustic wave, and λ_p denotes the wave length of the pump light in the optical fiber.

The stress or temperature variation would change the density of medium of the optical fiber, in consequence, both the refractive index and the velocity. Based on analysis of the Brillouin scattering spectrum, we can know that the Brillouin frequency shift is linear with both the strain and the temperature, which can be expressed as

$$\Delta\upsilon_B = C_\varepsilon\Delta\varepsilon + C_T\Delta T \tag{2}$$

where C_ε, C_T denote the strain and temperature sensitivity coefficients respectively, and $\Delta\varepsilon, \Delta T$ denote the strain and temperature increment loaded on the optical fiber. We have conducted Brillouin frequency shift-strain and Brillouin frequency shift-temperature calibration test in Lab, and the strain and temperature sensitivity coefficients are 0.05 MHz/με and 1.00 MHz/°C respectively [15,16].

It can be seen that the Brillouin frequency shift not only can response to strain, but also can feedback the temperature change from Eq. (2). In order to eliminate the measuring errors induced by the change of temperature, one distributed Brillouin temperature fiber optical sensor should be installed parallel to the distributed Brillouin strain fiber optical sensor in field applications. The temperature compensation method can be expressed as follow:

$$\Delta\varepsilon = (\Delta\upsilon_B - \psi\Delta\upsilon_{B1})/C_\varepsilon \tag{3}$$

where $\Delta\upsilon_{B1}$ ($\Delta\upsilon_{B1} = C_{TT}\Delta T$) and C_{TT} are the Brillouin frequency shift and the temperature sensing coefficient of Brillouin temperature fiber optical sensor, $\psi = C_T/C_{TT}$.

2.2. Introduction of conjugate beam method

Conjugate beam is defined as the imaginary beam with the same dimensions (length) as that of the original beam but load at any point on the conjugate beam is equal to the bending moment at that point divided by EI, and the conjugate-beam method (CBM) is an engineering method to derive the slope and displacement of a beam [17,18]. The relationships between the loading, shear and bending moment of real structure are given by:

$$\frac{d^2M}{dx^2} = \frac{dV}{dx} = -w(x) \tag{4}$$

where M is the bending moment; V is the shear; and $w(x)$ is the intensity of distributed load.

Similarly, we have the following:

$$\frac{d^2v}{dx^2} = \frac{d\theta}{dx} = \frac{M}{EI} \tag{5}$$

A comparison of two set of equations indicates that if $\frac{M}{EI}$ is the loading on an imaginary beam, the resulting shear and moment in the beam are the slope and displacement of the real beam. There are two major steps in the conjugate beam method. The first step is to set up an additional beam, called "conjugate beam," and the second step is to determine the " shearing forces " and " bending moments " in the conjugate beam.

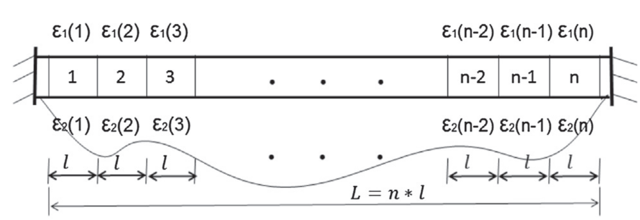
Knowing that the slope on the real beam is equal to the shear on conjugate beam and the deflection on real beam is equal to the moment on conjugate beam, the shear and bending moment at any point on the conjugate beam must be consistent with the slope and deflection at that point of the real beam. Fig. 1 shows the deflection of a real beam with fixed support determined by using the conjugate beam method and calculated by Eq. (3). In the Fig. 1, $\varepsilon_1(i), (i = 1 - n)$ and $\varepsilon_2(i), (i = 1 - n)$ denote the top and bottom strain of the given beam' the $i'th$ element, L and l are the length of the given beam and the element, and p denotes the node of element.

For the $p'th$ node ($p \le 2 \le n$), we have the following equations:

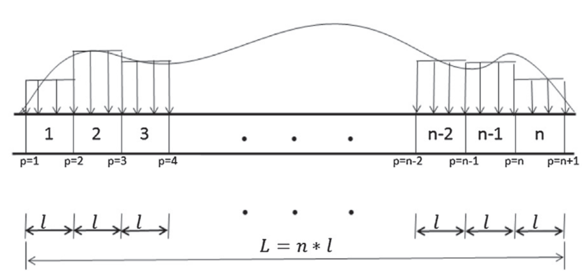
$$M_p = l^2 \sum_{i=1}^{p-1} \bar{q}_i (p - i - 1/2) \tag{6}$$

$$y_p = l^2 \sum_{i=1}^{p-1} \frac{\varepsilon_2(i) - \varepsilon_1(i)}{D_i} (p - i - 1/2) \tag{7}$$

where M_p is the bending moment of the $p'th$ node and y_p is the deflection of the $p'th$ node.



(a) Given beam



(b) Conjugate beam

Fig. 1. One given beam and its conjugate beam.